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The Constitution of the Solar Corona. III. By J. W. Nicholson, M.A., D.Sc.

The second paper * has shown that the fundamental physical basis of the coronal spectrum can lie in the quantum or unit theory of radiation, recently developed by Planck and others,† according to which interchanges of energy between systems of a periodic kind can only take place in certain definite amounts determined by the frequencies of the systems. The chemical basis of the greater part of the spectrum is, at the same time, a hypothetical substance called protofluorine. In the present paper we continue the investigation of the spectrum of this substance, with the notation of the previous papers, which it is not necessary to define again. Nearly all the important lines of the coronal spectrum, including those both of Dyson and Campbell, can be accounted for in this way. At the end of the last paper a summary ‡ of the lines of a certain character, due to the positively charged systems of protofluorine, was given. As will appear here, these lines are actually the "heads" of spectrum series of a peculiar type.

The first series in the coronal spectrum.—The quantum theory has apparently not been put forward as an explanation of "series" spectra, consisting of a large number of related lines given by a comparatively simple atom. Yet, in the belief of the writer, it furnishes the true explanation in certain cases, and we are led to

* *Monthly Notices*, June 1912.

† Planck, *Ann. der Phys.*, 1903 *et seq.*; Larmor, Bakerian Lecture, 1908; Poincaré, *Journ. de Phys.*, Jan. 1912.

‡ The last sentence should have *principal lines* instead of *lines*.

suppose that lines of a series may not emanate from the same atom, but from atoms whose internal angular momenta have, by radiation or otherwise, run down by various discrete amounts from a standard value. For example, in this view there are various kinds of hydrogen atom, identical in chemical properties and even in weight, but different in their internal motions.

An atom with only two electrons, according to the theory worked out by Sir J. J. Thomson,* has a comparatively rapid rate of radiation. If it loses its energy by definite amounts, instead of in a continuous manner, it should show a series spectrum with lines corresponding to each of the stages. Moreover, its incapacity for radiating in a continuous way would secure sharpness of the lines, so that Schott's theory of the expanding electron ceases to be necessary for an explanation of sharp lines.

In the case of a simple ring system such as protofluorine, with three electrons missing, the nature of this series can be ascertained at once. For if the ratio E of energy to frequency—a definite number of quanta—is expressed in a certain system of units, the principal wave-length for two electrons is always, in tenth-metres,

$$\lambda = (\tfrac{1}{2}\mathrm{E})^3/(\nu - \tfrac{1}{4}),$$

where $\nu = 5$ for protofluorine. This was proved in the last paper.† Thus at any stage in the radiation of the charged atom the number of quanta present is proportional to the cube root of the emitted wave-length. Accordingly, the series we seek is such that the cube roots of the wave-lengths differ by a constant quantity. It is noteworthy that this property seems to be possessed by many of the strongest lines in the vacuum-tube spectrum of hydrogen—a fact which may indicate that a ring of two or more electrons forms part of the structure of the hydrogen atom.

Now the principal line of protofluorine with two electrons was shown in the last paper to be $\lambda 5073$. The line is weak, and its companions in the series of which it should be a "head" will also be weak. Its wave-length corresponds to $\mathrm{E} = 97{\cdot}107$ in the system of units previously adopted.

Decreasing E by successive amounts equal to 2·2446, we get a series of lines given by

$$\lambda = (48{\cdot}553 - 1{\cdot}222n)^3/(4{\cdot}75)^2$$

with wave-lengths

	$n=0$	$n=1$	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$
$\lambda =$	5073	4725	4400	4086·5	3788	3506	3238
$\lambda' =$	5073	4725	4400	4087·4	...	3505	...

* *Phil. Mag.*, Dec. 1903. † *Loc. cit.*

The values of λ' are those of wave-lengths given by Dyson * as the results of three expeditions. All the lines are weak, and they correspond so closely to the values of λ that they furnish very strong evidence of the existence of the series. The value of the constant decrement of E will be discussed later in the paper. The line 3238 is outside the range of spectrum observed.

The impacts experienced by atoms.—It follows from the present theory of the corona, which regards it as made up of atoms whose vibrations in their own planes are not all stable, that a constant interchange of electrons is taking place. Thus an atom which at some point has been reduced to two electrons, and has radiated a number of quanta, may afterwards become more nearly neutral, with less angular momentum than its normal value. Accordingly other atoms with a sufficient number of electrons to prevent radiation in their present state, may exhibit series spectra on account of their previous history, even if radiation of an atom itself be the sole cause of a loss of energy.

But in reality these losses may also occur on account of impacts, so that such series may be expected from atoms which have always had more than two electrons.

We can form a rough estimate of the probable relative intensities of the sets of series on general grounds. The impacts are, of course, due to free electrons. If such a free electron falls on an atom which is positively charged, it will be retained in many cases, and the system will form into a ring with the appropriate number of quanta. Thus positively charged atoms should not show strong series, although the "head" of the series should be strong. Only in the case of two electrons, where radiation is important, should the series show many members.

But if an electron impinges on a negatively charged system, it must experience some repulsion, and the energy concerned in such repulsion may affect the atom, so that strong series may be shown by negatively charged systems,—especially in the presence of a large excess of free electrons, for example in a negatively charged corona.

A neutral atom will ordinarily remain unaffected by the passage of stray electrons, only becoming ionised by virtue of its own unstable vibrations. Probably it should not give a visible series.

Negatively charged atoms.—We now take up the consideration of negatively charged atoms, which were neglected in the second paper. Leaving out the spectral lines already interpreted, the following still await explanation. We include the lines recorded with certainty by Campbell,† which are absent from Dyson's table. One of them, $\lambda 3602{\cdot}3$, is stronger, in Campbell's spectrum, than the green coronal line $\lambda 5303$.

* *Phil. Trans.*, 1906, A, vol. ccvi., p. 451.
† *Lick Obs. Bull.*, No. 131, p. 11.

λ	Intensity.	Date.	Observer. C = Campbell. D = Dyson.
5535·8	2	1905	D
5303·1	20	1901, 1905	D, etc.
5117·7	2	1905	D, C
4779	1	1900	D
4722		1900	D
4566	6	1900, 1901	D, etc.
4359	4	1900	D
4130		1900	D
3891		1901	D
3642·5	2, 5	1900, 1905	D, C
3628·8	2	1905	C
3602·3	15	1905	C
3534	2	1905	C
3461	1	1900	D
3454	9	1901	D, C, etc.
3361 3357·5	1	1901, 1905	D, C
3328	5	1905	C
3288		1905	C

Some of Campbell's very doubtful lines are omitted. Certain of the above lines have also been obtained by other observers (Lockyer, Huff). The table contains 18 lines. The number excluded, as having received a satisfactory interpretation, is 11.

Protofluorine with six electrons.—The vibrations in the plane of the atom, of Class I., are important in the case of negatively charged systems, for they frequently appear in the visible range of the spectrum. Moreover, in the present case, if we recollect that the principal lines (higher in wave-length than those of any transverse vibration) are, for the various systems,

$$n = 2, \quad \lambda = 5073$$
$$n = 3, \quad \lambda = 4586$$
$$n = 4, \quad \lambda = 4231$$
$$n = 5, \quad \lambda = 3987$$

it is evident that the principal line moves towards the violet as the number of electrons increases. The principal line for six electrons will therefore have a wave-length less than λ3987. By the first paper * we thus deduce that the transverse vibrations all have wave-lengths less than (3987)/(1·255), or about 3100. If therefore any but the principal line can be seen as the head of a series, it must be due to a vibration in the plane of the atom. The

* *Monthly Notices*, Dec. 1911, p. 146.

suggested vibrations for $n = 6$ in the first paper thus do not survive a more searching examination.

The vibrations of Class I. in the plane of the atom of six electrons are given, to a first approximation, by the quartic

$$(x^2 + 3{\cdot}8702)(x^2 - 0{\cdot}85796) = (2x - 0{\cdot}21513)^2$$

or

$$x^4 - 0{\cdot}98776x^2 + 0{\cdot}8605x - 3{\cdot}2612 = 0$$

where $x = q/\omega$. The values of the two real roots are

$$x = 1{\cdot}4195, \quad -1{\cdot}6492.$$

These must be corrected on account of the mass M of the nucleus. The correction, after some labour, is derived from the formula on page 689 of the second paper, and in the second case becomes

$$-5{\cdot}588m/\mathrm{M},$$

so that the vibration gives, with reference to an observer,

$$q/\omega = 0{\cdot}6492 + 5{\cdot}588m/\mathrm{M}.$$

Guided by the results of the second paper, we may suppose that the atomic weight is about 2, so that $m/\mathrm{M} = 0{\cdot}000273$, using the experimental value for hydrogen. Thus

$$q/\omega = 0{\cdot}6507,$$

and the position of the principal line is such that this vibration should be in the visible spectrum.

The following pairs of lines satisfy this ratio closely:

$\lambda 3602{\cdot}3$ and $\lambda 5535{\cdot}8$
$\lambda 3328{\cdot}2$ and $\lambda 5117{\cdot}7$

and give a hint of the presence of two series, for this is a case in which strong series may be expected. The *exact* value of m/M necessary to bring coincidence between calculated and observed values is

$$m/\mathrm{M} = 0{\cdot}000279, \quad q/\omega = 0{\cdot}6508,$$

and the fact that it brings coincidence in *both* cases serves as a proof of the existence of two series in a constant ratio. The atomic weight of protofluorine must be also very nearly 2.

An examination of the remaining coronal lines establishes the presence of these series. The cube roots of the wave-lengths in any one series must differ by constants. The following are the known members of the series:—

Series I.	$\lambda = 3891$	$\lambda^{\frac{1}{3}} = 15{\cdot}728$	$0{\cdot}399$
	$\lambda = 3602{\cdot}3$	$\lambda^{\frac{1}{3}} = 15{\cdot}329$	
	$\lambda = 3328{\cdot}2$	$\lambda^{\frac{1}{3}} = 14{\cdot}930$	$0{\cdot}399$

Series II.

$\lambda = 5535{\cdot}8$	$\lambda^{\frac{1}{4}} = 17{\cdot}690$	}	$0{\cdot}457$
$\lambda = 5117{\cdot}7$	$\lambda^{\frac{1}{4}} = 17{\cdot}233$	}	
$\lambda = 4722$	$\lambda^{\frac{1}{4}} = 16{\cdot}777$	}	$0{\cdot}456$

The existence of $\lambda 4722$ indicates that at least one more member of the stronger first series is present, if it could be observed so far in the ultra-violet. Its wave-length is

$$\lambda = 3068,$$

and it should be moderately strong.

The "head" of the first series is $\lambda 3891$, which is weak, showing that only a small proportion of the negatively charged atoms have failed to change their energy by collision with electrons.

The great strength of some of these lines is in accordance with the now generally accepted opinion that the corona is, on the whole, negatively charged.

The corrected value of the second root of the quartic is $1{\cdot}4195$, the correction being inappreciable in this case. Thus any line in Series I. above, divided by $0{\cdot}4195$, should give a spectral line, but all such lines are in the extreme infra-red.

The system has only one *transverse* vibration of a wave-length greater than 3000. This is the line $\lambda = 3093$, corresponding to $\lambda 3891$ as a principal line. But unless $\lambda 3891$ were stronger than usual, this line could not be seen even if this portion of the spectrum could be examined readily.

Vibrations of Class II. require little discussion, for the quartic to which they lead is

$$x^4 - 1{\cdot}3818x^2 + 0{\cdot}7636x - 8{\cdot}5083 = 0$$

with real roots both nearly equal to 2. Thus they cannot lead to vibrations in the visible spectrum, but only to very long and very short waves.

Finally, therefore, we obtain only 6 lines for the present system, in the observed range of spectrum—

λ	Intensity.	Observer.	λ	Intensity.	Observer.
3891		D.	5535·8	2	D.
3602·3	20	C.	5117·7	1	D.
3328	5	C.	4722		D.

and 17 of the 29 lines are now interpreted.

Protofluorine with seven electrons.—The approximate quartic defining vibrations of Class I. is

$$x^4 - 1{\cdot}0424x^2 + 1{\cdot}7948x - 5{\cdot}7578 = 0.$$

Only one root can lead to a vibration in the visible spectrum,

with the principal line, or head of the primary series, shorter than 3700. The final value of this root, when corrected for m/M, is

$$x = -1{\cdot}894,$$

giving to an observer a wave-length

$$\lambda = \lambda_0/(0{\cdot}894)$$

where λ_0 is the principal line.

Only one pair of lines in the known spectrum are in the proper ratio. These are λ3454, a strong line, and Campbell's line, given as doubtful, about λ3865. We find $(3454)/(0{\cdot}894) = 3863$. The intensities are in accord with the previous case, for the great intensity of λ3602 in Campbell's spectrum shows that a large excess of electrons is present in the corona, and we should therefore expect a strong line corresponding to seven electrons. The secondary series (Series II.) was weak in the last case also, and practically in the same intensity ratio to the first series as 3865 is to 3454.

Since λ3865 is so weak, no further lines of the series to which it must belong can be expected, and it is therefore difficult to pick out the primary series for seven electrons.

But a little examination shows that

$$\lambda 3628{\cdot}8, \quad \lambda 3454, \quad \lambda 3285$$

form a series of the cube-root type, where the first is moderately strong in Campbell's spectrum, the second very strong in Campbell's and Dyson's, and the third is within the experimental margin of error (for this part of the spectrum) of Campbell's doubtful λ3288. This is the most extreme line hitherto measured, and might be stronger in a suitable form of apparatus.

That this is the proper series for seven electrons will be confirmed in a succeeding section of this paper.

Thus the system with seven electrons gives the lines

$$\lambda 3628{\cdot}8, \quad \lambda 3454, \quad \lambda 3285, \quad \lambda 3865.$$

The energy relations of atoms.—Let us consider, on general grounds, the probable energy values for single-ring atoms which would be imposed by any form of quantum theory, without the attempt to give a physical explanation of that theory, which would involve a knowledge of the nature of the æthereal structure which constitutes an electron.

We shall take the theory in the very general form suggested by Larmor in his Bakerian lecture, according to which energy capable of transfer resides in "cells," a cell being any form of physical store-house. If E is the quotient of energy by frequency of atomic repetition, or number of quanta contained in the atom, we may by symmetry portion it out equally between the electrons. If there

are n electrons, E/n is the share of energy units belonging to each, or residing in the cells of which it is a part. Three kinds of cells may be imagined. In the first place, the electron is connected in some way with the positive nucleus, and all electrons being alike, the energy contained in this cell can be imagined as a function only of the nucleus. Let its value be A.

Secondly, there are n cells connecting any electron to any other. If each stores a number B of quanta, B is independent of n, and the energy in the cells is Bn quanta.

Thirdly, the electron has some relation to the æthereal structure, whether of elastic or other type, which fills the atomic interspaces, and which is crossed by $\frac{1}{2}n(n-1)$ linkages between electrons. We may thus expect the function E/n to contain a term

$$\tfrac{1}{2}Cn(n-1),$$

which should not, however, be large. Thus, in general, the law which should obtain for a given nucleus with a varying number of electrons is

$$E/n = \text{quadratic function of } n.$$

When the number of electrons exceeds the strength of the nucleus, the law may change, but its quadratic character should be preserved.

We shall find that the protofluorine systems already dealt with agree very completely with these conclusions.

Application to protofluorine.—In the second paper it was shown that E/n itself approximately followed a harmonic law for neutral and positively charged atoms. Thus

$$E/n = A + Bn$$

for n electrons, where A and B do not involve n. Though correct to 1 part in 1000, the law is not accurate. But the law

$$E/n = A + Bn + Cn^2 \qquad (A)$$

of the type indicated above, is accurately followed, and C is very small in comparison with A or B.

In Larmor's form of the unit theory the energy unit given by Planck is not regarded as ultimate, but, instead, it is the *differential* ratio of energy element to extent of cell which is in some way predetermined. We are therefore at liberty to subdivide Planck's unit, and, in fact, Nernst and Lindemann have already done this in their recent fruitful work on atomic heat.

The law which appears to regulate the energy of negatively charged systems may be expressed in the form, m being an integer,

$$(E/n)_{\nu-m} + (E/n)_{\nu+m} = 2(E/n)_{\nu} \quad (B),$$

or, *the mean of the quanta of two systems of equal positive and*

negative charges is the number of quanta in the neutral system, per electron.

In addition there are a series of values of the energy-content of a system like protofluorine with a given number of electrons. These values are equidistant.

The *normal* or principal lines of the protofluorine systems with positive charges are

$$n=5,\quad \lambda=3987{\cdot}1, \qquad n=4,\quad \lambda 4231,$$
$$n=3,\quad \lambda=4586, \qquad n=2,\quad \lambda 5073.$$

These are the "heads" of series. With λ in tenth-metres we shall find it convenient to write

$$Q=E/n=\lambda^{\frac{1}{3}}(\nu-\tfrac{1}{4}Sn)^{\frac{2}{3}}/(0{\cdot}06235),$$

where Q is the number of quanta per electron and its unit is that of Planck divided by 5!

For the four systems the values of Q become, the number of electrons appearing in the suffix,

$$Q_5=600,\quad Q_4=658\tfrac{1}{2},\quad Q_3=718,\quad Q_2=778\tfrac{1}{2},$$

and their differences

$$58\tfrac{1}{2},\quad 59\tfrac{1}{2},\quad 60\tfrac{1}{2}$$

are accurately harmonic, so that the law (A) is fulfilled.

It follows that the number of quanta for the atom with one electron, whose life is a small fraction of a second, is 840. This gives a wave-length

$$\lambda=(52{\cdot}374)^3/25=5746{\cdot}5$$

outside the observed range. It could never be a strong line.

Consider now the sequence of values of Q for protofluorine with two electrons. The constant decrement was 2·2446, or 1·1223 per electron. This is exactly 18 quanta with our present unit, and the possible values of Q for the system are

$$Q_2=778\tfrac{1}{2}-18r$$

where r is any integer.

Consider, finally, the negatively charged systems in the cases

$$n=6,\quad \lambda=3328{\cdot}2$$
$$n=7,\quad \lambda=3454.$$

Since

$$5-\tfrac{1}{4}S_6=3{\cdot}1726,\quad 5-\tfrac{1}{4}S_7=2{\cdot}6952$$

we find

$$Q_6=517,\quad Q_7=469\tfrac{1}{2}.$$

Associate with these the value of $Q_2=778\tfrac{1}{2}-36=742\tfrac{1}{2}$. Then

we may show that with $Q_5 = 600$, denoting the unchanged neutral atom, these values are in accord with the law (B) of negatively charged atoms, and at the same time with (A) or the harmonic difference property. For this property yields

$$(Q_2 - Q_3) - (Q_3 - Q_4) = (Q_3 - Q_4) - (Q_4 - Q_5)$$

or

$$3Q_3 - 3Q_4 = Q_2 - Q_5,$$

and the law of negative atoms demands

$$Q_4 = 2Q_5 - Q_6, \quad Q_3 = 2Q_5 - Q_7, \quad Q_3 - Q_4 = Q_6 - Q_7,$$

whence

$$Q_7 = \tfrac{1}{3}\{3Q_6 - Q_2 + Q_5\} = 469\tfrac{1}{2},$$

which is the value above.

This establishes the fact that the decrements on either side of the neutral atom are in accordance, and that λ3454, as a line of the system with seven electrons, is in accord with simple laws.

We can prove a similar correspondence for

$$\left.\begin{matrix} n = 7, \quad \lambda = 3628{\cdot}2, \\ Q_7 = 477\tfrac{1}{2} \end{matrix}\right\} \qquad \left.\begin{matrix} n = 6, \quad \lambda = 3602{\cdot}3 \\ Q_6 = 531 \end{matrix}\right\}$$

$$Q_2 = 778\tfrac{1}{2} - 18 = 760\tfrac{1}{2},$$

completing the demonstration that λ3628·2 is a member of the series with λ3454, although its companion lines are invisible. We can then deduce the other members of the series, λ3285 being the next, for the laws of Q are difference laws, and, if satisfied for two members of a cube-root series, are satisfied by all.

Corresponding values of Q_3 are

$$Q_3 = 2Q_5 - Q_7 = 730\tfrac{1}{2},\ 722\tfrac{1}{2},$$

and do not lead to known lines. The original conclusion that such lines for three and four electrons would not be visible enough, is thus confirmed.

At the same time, possible values of Q_8 are

$$Q_8 = 2Q_5 - Q_2,$$

and numerical values are $1200 - 778\tfrac{1}{2} \pm 18m$, with m integral. This gives lines at 3305, 2882, and below; and the first, which is the only one capable of observation, should be weak. The second might be strong.

In these circumstances it is impossible for lines corresponding to more than eight electrons to appear in the visible range. They are in the extreme ultra-violet.

The following 21 lines have now been interpreted:—

λ	Intensity.	No. of Electrons.	λ	Intensity.	No. of Electrons.
5535·8	2	6	3891		6
5117·7	2	6	3865		7
5073	1	2	3800·9	3	4
4725		2	3628·8	2	7
4722		6	3602·3	15	6
4586	4	3	3505		2
4400	1	2	3454	9	7
4311	2	3	3387·9	12	5
4231	5	4	3328·2	5	6
4087		2	3288		7
3987	3	5			

There is an important residuum of lines in the next table which have not been explained. Six of them are in Dyson's table, and the others, which are nearly all doubtful, in Campbell's.

Line.	Intensity.	Line.	Intensity.
5303·1	20	4359	4
4779	1	4322?	
4566	6	4130	
4415?		3642·5	2
4396?		3534	2
4382?		3461	1
...		3357·5	1

Campbell has also given doubtful lines, which he regards as Fraunhofer maxima, at λλ3731, 3715, 3695, 3651.

The green coronal line is included in this table and is not a protofluorine line. This substance is not the "coronium" of astrophysicists.

We may notice that the cube roots of the wave-lengths of three of the most important lines have constant differences, so that they probably have a like origin. These lines are λλ5303, 4359, 3534.

The Motion of the Solar System relatively to the Interstellar Absorbing Medium. By W. H. Pickering, Assoc. R.A.S.

While the interstellar absorbing medium may be simply the ether, yet the character of its selective absorption, as indicated by Kapteyn, is characteristic of a gas, and free gaseous molecules are certainly there, since they are probably constantly being expelled by the Sun and stars, and certainly in a smaller way by the planets and comets. This is further indicated by the fact that the younger stars seem to be more massive than the older ones.

If, however, the ether is capable of offering any resistance whatever to the passage of matter, then gaseous molecules would, in the countless ages of their existence as free independent bodies, certainly be moving with it. Therefore in such a case also the present investigation would relate to the motion of the solar system relatively to the ether.

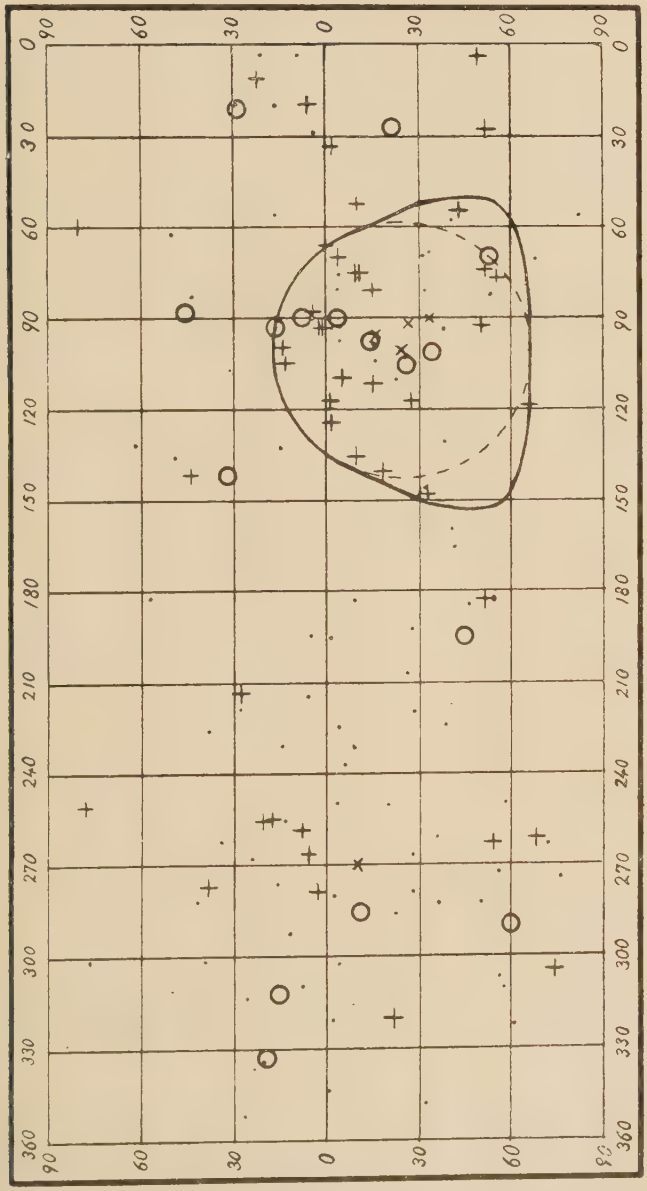
The most promising bodies in the solar system with which to investigate this question would seem to be the comets. Although 47 per cent. of those whose orbits are accurately known, and which recede far beyond the orbit of Neptune, are classed as parabolic, yet none of them are so in fact, since a parabolic orbit, like a perfect circle, is merely a mathematical conception. If these orbits were sufficiently well known they would all be divided between ellipses and hyperbolas. It is probable that a decided majority move in ellipses, and follow the Sun through space.

If now there were an absorbing and resisting medium in space, since the mass of a comet is much less in proportion to its surface than that of the Sun, it is clear that, given sufficient time, the aphelia of all the comets of long period would tend to fall behind the Sun in its path, and should be concentrated towards what we may call the Sun's "anti-apex with regard to the medium."

While this process was going on, however, this shifting of the aphelia would take place with different velocities in different areas of the sphere, most slowly near the apex and anti-apex of the Sun's motion, and most rapidly at 90° from these directions. We should accordingly expect to find comparatively few cometary aphelia in this latter belt.

If the comet had no gaseous envelopes about its component meteors, the effect upon it would be less marked than if these envelopes were extensive. Most comets are visible only by the electric illumination of these envelopes or atmospheres, as is shown by their spectra. The comet 1889 I. was traced to a distance of 8·2 units from the Sun. Whether the cometary atmospheres remain gaseous at still greater distances, or whether at aphelion they ultimately solidify, we have no means of knowing. At any rate, the more extensive the gaseous envelope, that is, the more brilliant the comet, the more marked should be the coincidence with the anti-apex of the Sun as here defined.

In the writer's recent volume on Cometary Statistics, *Harvard*



Cometary Aphelia.—W. H. Pickering.

Annals, 61, Part III., the cometary orbits are divided into various classes according to their aphelion distances or their parabolic or hyperbolic character. In the figure are shown the longitudes and

latitudes of the aphelia of all the parabolic orbits, and of all the orbits of very great aphelion distance, which are well determined, and which therefore belong to Classes D, E, and F. The telescopic comets are indicated by dots, the moderately bright naked-eye comets by crosses, and the brilliant comets by circles. There are 87 dots, 44 crosses, and 16 circles.

The dots are distributed with reasonable uniformity, one-half of them being included in a circular area covering about one-third of the total surface of the sphere. The crosses and circles, on the other hand, are much more unevenly spaced, 30 out of the 60 being concentrated within a circular area 42° in radius, which therefore contains about 13 per cent., or one-eighth the total area of the sky. The dotted line shows a circle of this radius, but when represented upon this projection it assumes a bell-shaped form, as shown by the full line. The chance that this concentration should be due to accident is only one in many thousands, and is too small to be considered.

The centre of the circle of maximum concentration of the faint comets lies in $\lambda = 270°$, $\beta = -9°$, the centre of the circle of concentration of the bright ones in $\lambda = 101°{\cdot}2$, $\beta = -24°{\cdot}4$. The centre of gravity of the aphelia of these bright comets is located in $\lambda = 97°{\cdot}2$, $\beta = -16°{\cdot}3$. It is shown in the volume above mentioned that the aphelia of most of the very eccentric orbits lie near two great circles of the sphere, and an explanation is offered for the southerly tendency of the aphelia. The circles themselves intersect near the centre of the circular area above shown, but that does not account for the difference between the distribution of the faint and bright comets, and only in part for their marked concentration at opposite portions of the sphere.

The Sun's anti-apex with regard to the stars, including both streams, lies, according to Boss, in $\lambda = 90°{\cdot}5$, $\beta = -34°{\cdot}3$. According to Campbell, from his spectroscopic measurements, it lies in $\lambda = 92°{\cdot}0$, $\beta = -27°{\cdot}5$. Each of these points is indicated on the map by a $\times$. Of 26 hyperbolic orbits, 9 of the corresponding comets were bright enough to be visible to the naked eye, but 3 of these probably moved originally in parabolic orbits. Of the remaining 6, only 1 aphelion lies within the circular area.

It would therefore seem that the aphelia of the brighter elliptical comets do tend to concentrate in a particular area of the sky, and that this anti-apex with regard to the resisting medium coincides pretty closely with the anti-apex with regard to the stars.

That the deviation between them is not due to accidental error, however, a glance at the map makes evident, since a circle drawn from either of the other $\times$'s as a centre would be manifestly erroneously located. The aphelia of 58 bright comets whose orbits are not well known, having appeared in most cases prior to the year 1700, and which are grouped therefore in Class I., give a centre still farther to the east, near longitude 110°. Their concentration is not so marked as for the better-known orbits, 19

out of 58 falling within a circle of the same size as that here shown, while 15 of them fall within the present circle.

Two explanations naturally suggest themselves, one or both of which may be correct, for the deviation between the results deduced from the stars and those deduced from the comets. One explanation is that the absorbing medium is not stationary with regard to the stars as a whole, and the other that the Sun is moving in a curve rather than a straight line, the comets indicating a region from which the Sun has formerly been moving. The result, based on the orbits of the earlier comets, can hardly be looked upon as confirmatory of this latter suggestion, since the change indicated by it is too rapid to be plausible, and, moreover, is due largely to three bright comets which appeared prior to the year 800 A.D., and whose aphelia are therefore rather uncertain.

On the other hand, the line of bright comets beginning with the great comet of 1882, $\lambda = 101^\circ{\cdot}6$, $\beta = -35^\circ{\cdot}2$, and extending along the ninetieth meridian to $\lambda = 89^\circ{\cdot}4$, $\beta = +46^\circ{\cdot}3$, with fainter comets on either side, radiating as it were from the southern end of the line, rather suggests a continuous change in the direction of the solar motion. This line, we may note, is inclined at an angle of about 20° to the direction of the Milky Way, crossing it in latitude +16°. It is true the head of the line is 10° east of the solar anti-apex with regard to the stars, but this we may perhaps assign to the other cause, the drift of the stars with regard to the absorbing medium. However, with two possible explanations of the deviation, we must clearly wait for further light before deciding upon their relative importance, and can merely conclude, therefore, that the solar motion relatively to the resisting medium differs somewhat in direction, but not very greatly, from its motion relatively to the stars.

On the Derivation of the Constants for the two Star-Streams. By J. C. Kapteyn, Assoc. R.A.S., with the co-operation of Dr. H. A. Weersma.

In two lectures, the one before the Congress at St. Louis in 1904, the other before the British Association in South Africa in 1905, I have communicated some of the elements of the two great star-streams without publishing at the same time the solution which led to these elements. I certainly intended to do so later, but as the method leads to very laborious calculations as soon as we wish to make a *detailed* comparison with the observations, I hoped at some future time to be able either to simplify it or replace the method by another which would be more commodious. Before I found leisure, however, to take up this task, Eddington published his solution. The elegance and convenience of his method leaving nothing to be desired, I provisionally gave up the plan of publishing my method at all. Afterwards Dyson published another method of exquisite simplicity, and Schwarzschild gave his well-known

beautiful method, which probably is the most convenient of all. There thus would be no use in publishing a more cumbrous method, were it not for the two following facts:—

First.—Eddington, Dyson, and Schwarzschild all make the derivation of the stream elements exclusively dependent on the *number* of proper motions in different position angles, whereas in my method the amount of the proper motion plays a part.

Second.—The hypotheses from which Eddington and Schwarzschild start are different. The present method may help to settle the question which of the two must be nearest the truth.

These considerations have revived my plan to publish my results in the form in which they were arrived at some eight years ago. Other matters, however, have continually interfered with the execution of this project, and might still have prevented it had not Dr. Weersma, on the appearance of Eddington's recent work relating to the second of the two points just mentioned, generously offered to collect and arrange my notes on the subject, and to prepare the whole for the press. I have gladly availed myself of this offer, and wish to express my most cordial thanks for his kind and skilful co-operation.

1. *Definitions and notation.*—First consider a number of stars in the point S of space, and suppose the solar system to be at rest. Let (fig. 1)

O be the position of the observer,
Ω a plane through S,
S Z the line O S prolonged,
S X the projection on Ω of the line S-antapex,
S Y a line at right angle to the former in the plane Ω,
S V, S W the line towards the true vertex and its projection on Ω,
S P $= s$ and S Q the linear peculiar motion in space of a star and its projection,
Δx, Δy the projection of S P on the x- and y-axes,
$\sum_0^\pi \Delta x$, etc., the sum of the Δx's making with the x-axis angles between o and π, etc.,
$\left[\Delta x\right]_0^\pi$, etc., the average values of these same quantities.

Let further (see fig. 1)

$$\phi = \text{V S P} \qquad \gamma = \text{W S X}$$
$$\sigma = \text{Z S P} \qquad \psi = \text{Q S W}$$
$$\lambda' = \text{V S Z} \qquad \rho = \text{O S}$$

while α, δ, A, D, A′, D′ represent the co-ordinates on the sphere of the star at S, the apex, and the true vertex.

2. *Formulæ.* — According to the theory of star-streaming, the true star-motions (freed from the Sun's motion) favour two opposite directions, the directions of the true vertices. In order

to express the predilection analytically, we assume that the frequency of a motion making the angle ϕ with the direction of one of the vertices is proportional to $1 + \epsilon \cos 2\phi$. This, of course, implies the assumption of equality in number of the two "star-streams." For the rest we take the frequency of the amounts of motion for any particular value of ϕ in accordance with Maxwell's law. The easiest way of representing the distribution of the

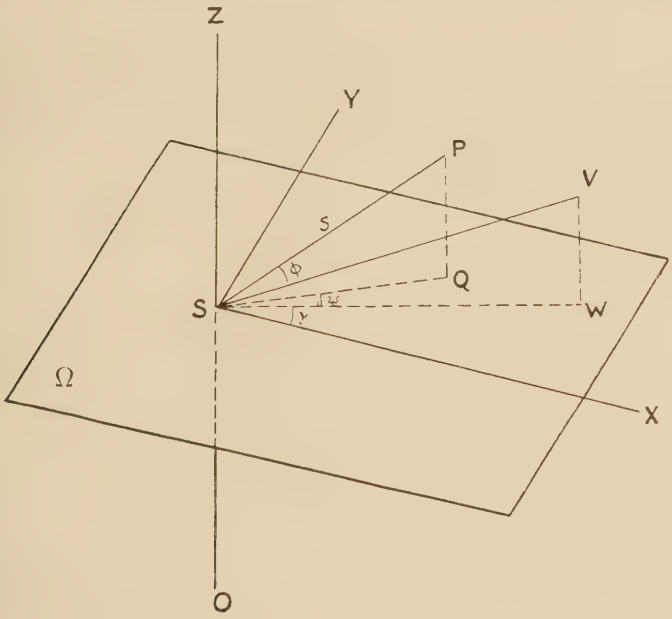


Fig. 1.—O, observer ; V, true vertex ; X, antapex.

direction is perhaps by considering the distribution of the positions of the *tops* P of the proper motions.

Let

Θ = the number of *tops* per unit of volume ;

then our assumption comes to putting

(1) . . . . $\Theta = Ce^{-h^2s^2}(1 + \epsilon \cos 2\phi)$

where C, h, and ϵ are constants to be determined from the observations. The quantity ϵ is a measure of the degree of preference for the direction of the vertices. $\epsilon = 0$ means that there is *no* preference ; the distribution will then, on our assumption, be wholly in agreement with Maxwell's law. ϵ *negative* expresses *averseness* to the direction of the vertices. For ϵ *positive* there is predilection. The distribution is best shown if in the different

directions we draw radii vectores proportional to the frequencies in these directions. The tops of these radii vectores will form a surface. For $\epsilon < 1$ there will be one continuous surface, which, for the smaller values of ϵ, does not diverge too much from an ellipsoid of revolution (Schwarzschild's theory). For increased values of ϵ the surface becomes more and more constricted in the neighbourhood of $\phi = 90°$. For $\epsilon > 1$ it will break up into two separate surfaces. We thus come nearer to Eddington's assumption.

The form adopted has some advantages therefore in regard to the question which of the two assumptions, those made by Schwarzschild and by Eddington, must be nearer to the truth.

The three constants C, h, and ϵ are not independent. The total number of *tops* is, of course, equal to the total number of stars at S. If this number is n, then

$$2\pi C \int_0^\infty s^2 e^{-h^2 s^2} ds \int_0^\pi (1 + \epsilon \cos 2\phi) \sin \phi d\phi = n,$$

from which

$$(2) \quad . \quad . \quad . \quad C = \frac{h^3}{\pi \sqrt{\pi}} \frac{3}{3 - \epsilon} n;$$

therefore

$$(3) \quad . \quad . \quad . \quad \Theta = \frac{n h^3}{\pi \sqrt{\pi}} \frac{3}{3 - \epsilon} e^{-h^2 s^2} (1 + \epsilon \cos 2\phi).$$

The determination, from the observations, of the remaining constants h, ϵ and the co-ordinates A′ and D′ of the vertex, was made in the way which was suggested by the results communicated in the British Association lecture, p. 5. It was there found that the quantities $x_R - x_L$ (which below will be designated by $\left[v\right]_0^\pi - \left[v\right]_\pi^{2\pi}$), which in the theory of random-distribution of the directions should all be zero, show on the contrary an astonishing amount of systematic variation. It was just the investigation of the law of this variation that finally led to the recognition of the phenomenon of star-streaming. It seems natural to use these same observed quantities as the basis for the derivation of the stream-constants. This was accordingly done; only, in order, if possible, to strengthen the determination, the perpendicular components τ of the proper motion were also considered.

We thus have to derive the values of $\left[v\right]_0^\pi$, $\left[v\right]_\pi^{2\pi}$, $\left[\tau\right]_0^\pi$, $\left[\tau\right]_\pi^{2\pi}$ in terms of the constants.

We have

$$(4) \quad . \quad . \quad . \quad . \quad \begin{aligned} \Delta x &= s \sin \sigma \cos (\psi + \gamma) \\ \Delta y &= s \sin \sigma \sin (\psi + \gamma). \end{aligned}$$

On the other hand, the number of *tops* P in an element of space is easily found to be

$$(5) \quad . \quad . \quad . \quad C s^2 e^{-h^2 s^2} (1 + \epsilon \cos 2\phi) \sin \sigma ds d\sigma d\psi;$$

or, writing

(6) . . . $\cos\phi = \cos\lambda'\cos\sigma + \sin\lambda'\sin\sigma\cos\psi$

(7) . . . $Cs^2e^{-h^2s^2}\{1-\epsilon+2\epsilon\cos^2\lambda'\cos^2\sigma$

$+4\epsilon\cos\lambda'\sin\lambda'\cos\sigma\sin\sigma\cos\psi+2\epsilon\sin^2\lambda'\sin^2\sigma\cos^2\psi\}\sin\sigma ds d\sigma d\psi$

Therefore

$$\sum_0^\pi \Delta x = C(1-\epsilon)\int_0^\infty s^3e^{-h^2s^2}ds\int_0^\pi \sin^2\sigma d\sigma\int_{-\gamma}^{\pi-\gamma}\cos(\psi+\gamma)d\psi$$
$$+2C\epsilon\cos^2\lambda'\int_0^\infty s^3e^{-h^2s^2}ds\int_0^\pi\cos^2\sigma\sin^2\sigma d\sigma\int_{-\gamma}^{\pi-\gamma}\cos(\psi+\gamma)d\psi.$$

(8) $+4C\epsilon\cos\lambda'\sin\chi\int_0^\infty s^3e^{-h^2s^2}ds\int_0^\pi\cos\sigma\sin^3\sigma d\sigma\int_{-\gamma}^{\pi-\gamma}\cos\psi\cos(\psi+\gamma)d\psi$
$$+2C\epsilon\sin^2\lambda'\int_0^\infty s^3e^{-h^2s^2}ds\int_0^\pi\sin^4\sigma d\sigma\int_{-\gamma}^{\pi-\gamma}\cos^2\psi\cos(\psi+\gamma)d\psi.$$

The corresponding expression for $\sum_0^\pi \Delta y$ is obtained by substituting $\sin(\psi+\gamma)$ for $\cos(\psi+\gamma)$.

Working out the integrals and taking account of (2),

$$\sum_0^\pi \Delta x = \frac{3n}{4}\frac{1}{h\sqrt{\pi}}\frac{\epsilon}{3-\epsilon}\sin^2\lambda'\sin 2\gamma,$$

$$\sum_0^\pi \Delta y = \frac{n}{2}\frac{1}{h\sqrt{\pi}}+\frac{3}{4}\frac{n}{h\sqrt{\pi}}\frac{\epsilon}{3-\epsilon}\left(\sin^2\lambda'\sin^2\gamma-\frac{1}{3}\right);$$

or, if we introduce the mean values, indicated by square brackets,

(9) $$\left[\Delta x\right]_0^\pi = \frac{3}{2}\frac{1}{h\sqrt{\pi}}\frac{\epsilon}{3-\epsilon}\sin^2\lambda'\sin 2\gamma.$$

(10) $$\left[\Delta y\right]_0^\pi = \frac{1}{h\sqrt{\pi}}+\frac{3}{2}\frac{1}{h\sqrt{\pi}}\frac{\epsilon}{3-\epsilon}\left(\sin^2\lambda'\sin^2\gamma-\frac{1}{3}\right).$$

In order to be able to substitute the observed proper motions for the $\Sigma\Delta x$ and $\Sigma\Delta y$, we have now to introduce the consideration of the Sun's motion through space. We will take the velocity of this motion as our unit of velocity. Let v, τ be the components of the total observed angular proper motion in the directions towards the antapex and at right angles to it, λ the distance on the sphere of S from the apex. We find at once

(11) . . . $$\rho v = \sin\lambda + \Delta x$$
$$\rho\tau = \pm\Delta y.$$

The sign of Δy will be taken such that $\rho\tau$ becomes alway positive. Considering that the angle which the total prope

motion on the sphere makes with the great circle towards the apex varies between 0° and 180°, respectively, 180° and 360° together with the angle X S Q (fig. 1) and that ρ is constant for the stars in S, we have

$$(12) \quad \begin{aligned} \rho\left[v\right]_0^{\pi} &= \sin\lambda + \left[\Delta x\right]_0^{\pi} \\ \rho\left[\tau\right]_0^{\pi} &= \left[\Delta y\right]_0^{\pi} \end{aligned}$$

and

$$(13) \quad \begin{aligned} \rho\left[v\right]_{\pi}^{2\pi} &= \sin\lambda + \left[\Delta x\right]_{\pi}^{2\pi} \\ \rho\left[\tau\right]_{\pi}^{2\pi} &= -\left[\Delta y\right]_{\pi}^{2\pi}, \end{aligned}$$

Therefore, as it is easily seen that

$$\left[\Delta x\right]_{\pi}^{2\pi} = -\left[\Delta x\right]_0^{\pi}, \left[\Delta y\right]_{\pi}^{2\pi} = -\left[\Delta y\right]_0^{\pi}$$

we have by (9) and (10), τ being always taken positively,

$$(14) \quad \begin{aligned} \rho\left[v\right]_0^{\pi} - \rho\left[v\right]_{\pi}^{2\pi} &= \frac{1}{h\sqrt{\pi}}\frac{3\epsilon}{3-\epsilon}\sin^2\lambda'\sin 2\gamma \\ \rho\left[\tau\right]_0^{2\pi} &= \frac{1}{h\sqrt{\pi}} + \frac{3}{2}\frac{1}{h\sqrt{\pi}}\frac{\epsilon}{3-\epsilon}\left(\sin^2\lambda'\sin^2\gamma - \frac{1}{3}\right) \end{aligned}$$

$$(15) \quad \rho\left[v\right]_0^{2\pi} = \sin\lambda,$$

and therefore by division

$$(16) \quad \frac{\left[v\right]_0^{\pi} - \left[v\right]_{\pi}^{2\pi}}{\left[v\right]_0^{2\pi}} = \frac{\frac{1}{h\sqrt{\pi}}\frac{3\epsilon}{3-\epsilon}\sin^2\lambda'\sin 2\gamma}{\sin\lambda}$$

and

$$(17) \quad \frac{\left[\tau\right]_0^{2\pi}}{\left[v\right]_0^{2\pi}} = \frac{\frac{1}{h\sqrt{\pi}} + \frac{3}{2}\frac{1}{h\sqrt{\pi}}\frac{\epsilon}{3-\epsilon}\left(\sin^2\lambda'\sin^2\gamma - \frac{1}{3}\right)}{\sin\lambda}.$$

These formulæ have been derived on the supposition that we have to do with stars at one and the same point of space. If now, however, we assume that the quantities A', D', h and ϵ are the same for the whole of space, the second members of (16) and (17) become independent of the position of the star. These

formulæ, therefore, will hold for the whole of the stars visible in any one region of the sky. If for the sake of brevity we put

$$(18)\quad \left\{\begin{aligned} \frac{\left[v\right]_0^{\pi} - \left[v\right]_{\pi}^{2\pi}}{\left[v\right]_0^{2\pi}} &= u \\ \frac{\left[\tau\right]_0^{2\pi}}{\left[v\right]_0^{2\pi}} &= t \\ \frac{1}{h\sqrt{\pi}}\,\frac{3\epsilon}{3-\epsilon} &= \alpha \\ \frac{1}{h\sqrt{\pi}} &= \beta \\ \sin^2\lambda' \sin 2\gamma &= \mathrm{H} \\ \tfrac{1}{2}\sin^2\lambda' \sin^2\gamma &= \mathrm{G}, \end{aligned}\right.$$

we have simply

$$(19)\quad \alpha \mathrm{H} = u \sin\lambda.$$

$$(20)\quad \beta + \alpha\left(\mathrm{G} - \frac{1}{6}\right) = t \sin\lambda.$$

We will further suppose that the co-ordinates A and D of the apex have been determined by means of a method that does not involve suppositions inconsistent with the equation (1), for example, by means of the method of Bravais. The quantities $u \sin\lambda$ and $t \sin\lambda$ may then be derived from the observed proper motions. H and G are functions of the unknown quantities A′ and D′. Formulæ for expressing H and G in A′ and D′ will be given presently. By the aid of these the determination of the quantities A′, D′, α and β may be carried out in two steps, viz. by deriving, I., a set of approximations A_0', D_0', α_0 and β_0 for these quantities; and II., a set of corrections $\Delta\mathrm{A}'$, $\Delta\mathrm{D}'$, $\Delta\alpha$ and $\Delta\beta$ to be added to the former in order to obtain the values for A′, D′, α and β best satisfying the equations of condition.

As to I., approximate values for A_0' and D_0' may be obtained in several ways, for instance in the way indicated in "Star-streaming" (*Report of the British Association for the advancement of Science*, 1905, p. 257, etc.). With these approximations for A and D′ we may then derive approximations H_0 and G_0 for H and G. Introducing all these approximate values in the equations of condition (19) and (20), these will yield by their solution approximate values for the constants α and β.*

* A first approximation for β is not really necessary As a matter of fact, however, we have first derived such a value.

As to II., approximate values A_0', D_0', α_0 and β_0 having been obtained, the corrections $\Delta A'$, $\Delta D'$, $\Delta\alpha$ and $\Delta\beta$ must be found by means of the differential equations

$$(21)\qquad \alpha_0\left(\frac{dH}{dA'}\right)_0\Delta A' + \alpha_0\left(\frac{dH}{dD'}\right)_0\Delta D' + H_0\Delta\alpha = u\sin\lambda - \alpha_0 H_0.$$

$$(22)\qquad \alpha_0\left(\frac{dG}{dA'}\right)_0\Delta A' + \alpha_0\left(\frac{dG}{dD'}\right)_0\Delta D' + \left(G_0 - \frac{1}{6}\right)\Delta\alpha + \Delta\beta = t\sin\lambda - \alpha_0 G_0 + \frac{1}{6}\alpha_0 - \beta_0.$$

In order to obtain the necessary values of H and G we first, in the spherical triangle North Pole—star—antapex, compute the angle χ at the star by the formulæ

$$(23)\qquad \begin{aligned} \sin\lambda\sin\chi &= -\cos D\sin(A-\alpha)\\ \sin\lambda\cos\chi &= -\cos\delta\sin D + \sin\delta\cos D\cos(A-\alpha)\end{aligned}$$
$$(\lambda \leq 180^\circ)$$

where $180^\circ - \lambda =$ the arc star-antapex.

We then find the quantities γ and λ' entering into the expressions (18) of H and G by the spherical triangle North Pole—star—true vertex, in which the sides are $90-\delta$, $90-D'$, λ', and the angles opposite to the two last $\chi-\gamma$ and $A'-\alpha$. Therefore

$$(24)\qquad \begin{aligned} \sin\lambda'\sin(\chi-\gamma) &= \cos D'\sin(A'-\alpha)\\ \sin\lambda'\cos(\chi-\gamma) &= \cos\delta\sin D' - \sin\delta\cos D'\cos(A'-\alpha'),\end{aligned}$$

after which we find H and G by the expressions (18).

The differential quotients were computed by differential formulæ and checked by computing H and G also: (*a*) with somewhat different value of A', and (*b*) with somewhat different value of D'.

3. *Application of the method.*—The materials used in the application of the present method are the corrected proper motions of the Bradley stars, as published in *Groningen Publ.* 9. The stars have been divided into 28 groups according to the galactic longitude and latitude (Table I.), and for each of these groups the quantities $u\sin\lambda$ and $t\sin\lambda$ have been calculated. In *Publ.* 9 the fainter components of double and multiple stars, the Hyades and Pleiades, were already excluded. We have here further excluded the stars of the Ursa group, β, γ, δ, ϵ, and ζ Ursæ majoris. Finally, 1 star of the first type and 28 of the second, all with excessive proper motions, have been omitted. Care was taken to omit approximately an equal percentage of the proper motions making the angles 0° to $\pm 30^\circ$, $\pm 30^\circ$ to $\pm 60^\circ$, etc., with the parallactic motion. It is expected that in this way the exclusion cannot have affected the results systematically. In order to lessen still further the influence of the very large proper motions, the stars of Spectrum-type I. have been taken with double weight. Table I. contains the data, obtained in this way, and

the weights adopted for the different groups; the latter have been taken generally proportional to the numbers of stars of the groups and to the values of $\sin^2 \lambda$ corresponding to the centres of the areas. From these data approximate values for α and β have been calculated by means of the equations of condition (19) and (20), adopting for the co-ordinates of the apex *

(25) . . $A = 273^\circ$ $D = +29^\circ{\cdot}5$,

and as approximate values for the co-ordinates of the true vertex

(26) . . $A_0' = 90^\circ$ $D_0' = +15^\circ$.

The values found are

(27) . . . $\alpha_0 = 1{\cdot}17$ $\beta_0 = 0{\cdot}84$.

With the aid of these approximate values of A_0', D_0', α_0 and β_0, the equations of condition (21) and (22) have been formed for each of the 28 areas. They are shown in Tables II. and III. The solution by least squares of the equations of Table II. led to the values

(28) . $A' = 92^\circ{\cdot}0 \pm 2^\circ{\cdot}0$† $D' = +18^\circ{\cdot}7 \pm 5^\circ{\cdot}2$
$\alpha = 1{\cdot}234 \pm 0{\cdot}055$.

In the equations of Table III. the unknown quantities are not well separable; moreover, the quantities $\Delta A'$ and $\Delta\alpha$ have small coefficients. These quantities were, therefore, taken from the solution of the equations of Table II. After that the solution yielded the values

(29) . $D' = +15^\circ{\cdot}3 \pm 6{\cdot}6$ $\beta = 0{\cdot}839 \pm 0{\cdot}043$.

Finally, the equations of condition of Table II. and Table III. have been combined into one solution. From the residuals obtained by substituting the results (28) and (29) into the equations of condition the following quantities were found for the probable errors corresponding with the unit of weight:

(30) . . . $r_0 = \pm 0{\cdot}152$ for Table II.
$r_0 = \pm 0{\cdot}108$ for Table III.

The squares of these quantities are nearly proportional to 2 and 1; for this reason the equations of condition from Table II. and those from Table III. have been combined with weights 1 and 2. The normal equations thus obtained are given in Table IV. Their solution leads to the values

(31) . $A' = 91^\circ{\cdot}4 \pm 1^\circ{\cdot}8$ $D' = +17^\circ{\cdot}9 \pm 4^\circ{\cdot}1$
$\alpha = 1{\cdot}232 \pm 0{\cdot}054$ $\beta = 0{\cdot}825 \pm 0{\cdot}033$.

* The values for the co-ordinates of the apex used here are those finally found in *Astron. Nachr.*, No. 3722, p. 17, and differ only little from those found in *Gron. Publ.*, No. 21, by means of the method of Bravais.

† The errors given are all probable errors.

Finally, adopting these we get by (18)

(32) . . $h = 0''.684 \pm 0''.027$ $\epsilon = 0.997 \pm 0.039$.

The value found for ϵ is practically $= 1.000$. Therefore, according to what has been said above, our solution is decidedly in favour of the *two*-stream theory as opposed to Schwarzschild's ellipsoidal theory.

Meanwhile, the uncertainty of the declination of the vertex is still undesirably large. It diverges considerably from an anterior, totally different, solution of the problem, of which it seems unnecessary to give details. The results there arrived at were

(33) . . $A' = 89^\circ.5 \pm 2^\circ.6$ $D' = +7^\circ.5 \pm 1^\circ.8$.

Careful considerations of the circumstances finally led us to adopt

(34) . . . $A' = 90^\circ 5$ $D' = +13^\circ.5$,

which values were first published in 1904, in a lecture before the congress at St. Louis. The theoretical values of $u \sin \lambda$ and $t \sin \lambda$ used in deriving the O – C of our tables have been computed with the constants (31). It seems hardly worth while to recompute them for the co-ordinates (33). As they stand, they show plainly how strongly the two-stream hypothesis has contributed to represent the observations. In the old theory of random-distribution of motions, $u \sin \lambda$ ought in each case to be zero. The observed values would therefore have to be considered as accidental deviations. On the same theory $t \sin \lambda$ ought to be constant, and the deviations from a mean value would represent the accidental deviations. The observed values have therefore been inserted in the table in a form that shows these deviations from a mean value.

In order to see more clearly what has been gained by the two-stream theory, we have, in Table I., to compare the values in the columns 6 and 7 with those of O – C in the columns 10 and 11. Calling Δ the residuals, p the weights, we find for the sum of the $p\Delta^2$

	Random-Distribution.	Two Star-Streams.
$u \sin \lambda$	18·66	1·25
$t \sin \lambda$	1·90	0·90[5]

In the case of the residuals for $u \sin \lambda$ the new theory has thus reduced the sum of the squares of the errors to one-fifteenth of its amount.

4. *Test of the theory by radial velocities.*—If the stars all moved exactly in the direction of the two great stream-lines, the peculiar radial velocity (*i.e.* the observed radial velocity freed from the Sun's motion through space) would be *zero* in the regions of the sky which lie at a distance of 90° from the true vertices. On the other hand, in the regions near the vertices, the peculiar motions of the stars would be wholly radial, and would be *positive* for the

stars belonging to the one stream, *negative* for those of the other. For regions further and further away from the vertices, therefore, observation would show a regular diminution in the average radial velocity (all the velocities being taken positive) from the average value of the total star-velocity at the vertices, down to *zero* for regions 90° distant from those points.

Since the stars do *not* all move exactly in the direction of the stream-lines, such extreme variation will not obtain. Still, however, there will remain a regular change, the law of which can be easily derived from the preceding theory. The comparison of the theoretical change with that found by observation, must furnish a perfectly independent, and consequently extremely valuable, test of the theory.

We thus have to find, in the first place, how, according to our theory, the average peculiar radial velocity $\Delta\rho$ changes with λ' (distance on the sphere from vertex).

With the preceding notation we have

$$(35) \quad . \quad . \quad . \quad . \quad \Delta\rho = s\cos\sigma.$$

Let $[\Delta\rho]$ represent the average value of the $\Delta\rho$, these quantities being all taken *positive*. Since evidently the absolute value of the average *positive* and average *negative* $\Delta\rho$ is the same, we have, taking in the first place only stars at one and the same distance from the sun

$$\begin{aligned} n[\Delta\rho] = {} & 2C(1-\epsilon)\int_0^\infty s^3 e^{-h^2s^2} ds \int_0^{\frac{1}{2}\pi} \sin\sigma\cos\sigma d\sigma \int_0^{2\pi} d\psi \\ & + 4C\epsilon\cos^2\lambda' \int_0^\infty s^3 e^{-h^2s^2} ds \int_0^{\frac{1}{2}\pi} \sin\sigma\cos^3\sigma d\sigma \int_0^{2\pi} d\psi \\ & + 8C\epsilon\sin\lambda'\cos\lambda' \int_0^\infty s^3 e^{-h^2s^2} ds \int_0^{\frac{1}{2}\pi} \sin^2\sigma\cos^2\sigma d\sigma \int_0^{2\pi} \cos\psi d\psi \\ & + 4C\epsilon\sin^2\lambda' \int_0^\infty s^3 e^{-h^2s^2} ds \int_0^{\frac{1}{2}\pi} \sin^3\sigma\cos\sigma d\sigma \int_0^{2\pi} \cos^2\psi d\psi. \end{aligned}$$

The integrals offer no difficulty. We get

$$(36) \quad . \quad . \quad . \quad n[\Delta\rho] = C\frac{\pi}{2h^4}(2-\epsilon\sin^2\lambda').$$

The second member of (36) being independent of the distance of S from O, we may extend in the first member the Σ over all stars on the line O Z without changing the second member; only the number n will change. We thus have, if now $[\Delta\rho]$ represents the average value of *all* the $\Delta\rho$'s,

$$(37) \quad . \quad . \quad [\Delta\rho] = \frac{1}{h\sqrt{\pi}}\frac{3}{3-\epsilon}\left(1-\frac{1}{2}\epsilon\sin^2\lambda'\right).$$

With the values (32) of the constants this becomes

(38) . $[\Delta\rho] = 1\cdot24 - 0\cdot62\sin^2\lambda' = 0\cdot62(1 + \cos^2\lambda')$,

and assuming 20·0 kil. for the sun's velocity,

(39) . . $[\Delta\rho] = 12\cdot4(1 + \cos^2\lambda')$ kil. per second.

The constants are very slightly different from those adopted in the *Report of the British Association* for 1905, p. 9. How observations are represented may be seen in that paper.

TABLE I.

Nr. Reg.	Limits of gal. long.	Limits of gal. lat.	Mean α.	Mean δ.	$u \sin\lambda$.	$t \sin\lambda$ $= +0\cdot79+$.	Number of Stars.	Weight.	O − C. $u \sin\lambda$.	O − C. $t \sin\lambda$
	° °		h m	°						
1	325–4	−90° to −40°	21 43	−23·5	+0·29	−0·05	33	0·3	−0·44	−0·08
2	5–44		22 34	−10·0	+0·96	+ ·28	92	1·4	− ·04	+ ·16
3	45–84		23 44	+ 6·0	+1·58	+ ·36	72	1·1	+ ·35	+ ·21
4	85–124		1 12	+ 6·0	+1·12	+ ·41	83	1·4	− ·01	+ ·28
5	125–164		2 39	− 2·5	+0·73	+ ·19	55	0·7	− ·03	+ ·08
6	325–4	+41° to +90°	15 5	+14·0	−0·62	+ ·42	53	0·4	+ ·07	+ ·28
7	5–44		15 24	+33·0	−0·96	+ ·32	44	0·3	+ ·02	+ ·19
8	45–84		13 41	+48·7	−0·36	− ·40	29	0·3	+ ·64	− ·43
9	85–124		11 30	+57·7	−1·31	− ·02	37	0·6	− ·39	+ ·04
10	125–164		10 5	+40·3	−0·64	+ ·01	66	1·1	+ ·21	+ ·04
11	165–204		9 55	+17·7	−0·51	− ·06	83	1·1	+ ·29	− ·12
12	205–244		11 12	+ 4·8	−1·35	+ ·02	74	1·1	− ·20	− ·12
13	245–284		12 37	− 3·3	−1·04	+ ·06	55	1·0	+ ·18	− ·08
14	285–324		13 52	− 2·1	−0·49	− ·11	46	0·6	+ ·50	− ·23
15	325–4	+1° to +40°	16 56	− 2·5	−0·22	− ·05	99	0·6	− ·23	+ ·03
16	5–44		18 17	+30·0	0·00	− ·76	102	0·0	− ·59	− ·84
17	45–84		19 56	+65·5	+0·09	+ ·18	103	0·7	− ·39	+ ·31
18	85–124		4 42	+76·0	−0·31	− ·14	106	1·8	− ·43	+ ·02
19	125–164		6 58	+33·3	+0·10	− ·13	132	2·1	+ ·20	+ ·02
20	165–204		8 4	+ 9·0	−0·12	− ·06	116	1·0	+ ·01	− ·03
21	205–244		9 40	−15·5	−0·66	− ·03	52	0·4	+ ·24	− ·18
22	285–324		15 17	−22·3	−0·92	− ·31	69	1·3	− ·41	− ·29
23	325–4	−39° to 0°	19 19	−17·0	+0·16	+ ·08	107	1·1	+ ·12	+ ·19
24	5–44		20 36	+10·7	+0·26	+ ·06	156	1·1	− ·12	− ·06
25	45–84		22 32	+39·0	+1·14	− ·07	117	1·3	− ·07	− ·14
26	85–124		2 5	+43·8	+1·07	− ·13	144	3·1	+ ·27	− ·10
27	125–164		4 32	+20·1	+0·07	− ·24	160	2·5	− ·08	− ·14
28	165–204		5 35	− 8·5	−0·58	+ ·58	119	0·4	− ·34	+ ·70

TABLE II.

Equations of Condition derived from the quantities u sin λ.

Nr. Reg.					O−C.
1	−1·027ΔA′	−0·363ΔD′	+0·639Δα	= −0·46	−0·44
2	−0·797	−0·199	+ ·846	= − ·03	− ·04
3	−0·086	+0·064	+ ·998	= + ·41	+ ·35
4	+0·688	−0·034	+ ·896	= + ·07	− ·01
5	+1·147	−0·335	+ ·597	= + ·03	− ·03
6	−1·274	+0·259	− ·542	= + ·01	+ ·07
7	−0·936	−0·480	− ·740	= − ·09	+ ·02
8	+0·559	−0·645	− ·926	= + ·72	+ ·64
9	+1·350	−0·308	− ·739	= − ·45	− ·39
10	+1·148	+0·087	− ·685	= + ·16	+ ·21
11	+0·993	+0·359	− ·691	= + ·30	+ ·29
12	+0·486	+0·056	− ·951	= − ·24	− ·20
13	−0·376	−0·033	− ·972	= + ·10	+ ·18
14	−0·935	+0·156	− ·784	= + ·43	+ ·50
15	−0·216	+0·765	+ ·043	= − ·27	− ·23
16	−0·801	+0·978	+ ·451	= − ·53	− ·59
17	+2·080	+0·528	+ ·298	= − ·26	− ·39
18	+1·990	+0·152	+ ·032	= − ·35	− ·43
19	+0·768	+0·301	− ·122	= + ·24	+ ·20
20	+0·746	+0·832	− ·168	= + ·08	+ ·01
21	+1·034	+0·054	− ·758	= + ·23	+ ·24
22	−1·055	+0·362	− ·404	= − ·45	− ·41
23	−0·417	−0·611	+ ·078	= + ·07	+ ·12
24	−1·286	−0·590	+ ·376	= − ·18	− ·12
25	+0·262	+0·675	+ ·943	= + ·04	− ·07
26	+1·326	+0·158	+ ·601	= + ·37	+ ·27
27	+0·649	−0·449	+ ·132	= − ·08	− ·08
28	−0·489	−0·691	− ·147	= − ·41	− ·34

Normal Equations.

+22·067ΔA′	+2·443ΔD′	+0·975Δα	= +0·991
+ 2·443	+3·126	−0·077	= +0·283
+ 0·975	−0·077	+7·708	= +0·523

TABLE III.

Equations of Condition derived from the quantities t *sin* λ.

Nr. Reg.					O-C.
1	−0·401ΔA′	+0·355ΔD′	−0·005Δα+Δβ	= −0·09	−0·08
2	−0·260	+ ·516	+ ·058	= + ·16	+ ·16
3	+ ·044	+ ·584	+ ·078	= + ·22	+ ·21
4	+ ·185	+ ·555	+ ·060	= + ·29	+ ·28
5	+ ·241	+ ·526	+ ·046	= + ·09	+ ·08
6	+ ·143	+ ·570	+ ·067	= + ·29	+ ·28
7	− ·202	+ ·546	+ ·069	= + ·19	+ ·19
8	− ·402	+ ·352	− ·008	= − ·44	− ·43
9	− ·398	+ ·196	− ·073	= + ·02	+ ·04
10	− ·413	+ ·260	− ·046	= + ·02	+ ·04
11	− ·369	+ ·421	+ ·020	= − ·13	− ·12
12	− ·140	+ ·571	+ ·076	= − ·12	− ·12
13	+ ·098	+ ·581	+ ·073	= − ·07	− ·08
14	+ ·205	+ ·546	+ ·056	= − ·22	− ·23
15	+ ·326	+ ·158	− ·109	= + ·03	+ ·03
16	+ ·322	+ ·458	+ ·016	= − ·83	− ·84
17	+ ·166	+ ·039	− ·155	= + ·31	+ ·31
18	+ ·021	+ ·001	− ·166	= + ·01	+ ·02
19	− ·199	+ ·025	− ·150	= ·00	+ ·02
20	− ·413	+ ·250	− ·050	= − ·05	− ·03
21	− ·042	+ ·589	+ ·080	= − ·17	− ·18
22	+ ·376	+ ·271	− ·063	= − ·28	− ·29
23	− ·316	+ ·087	− ·120	= + ·17	+ ·19
24	− ·261	+ ·516	+ ·059	= − ·06	− ·06
25	+ ·335	+ ·442	+ ·008	= − ·13	− ·14
26	+ ·362	+ ·224	− ·083	= − ·08	− ·10
27	+ ·295	+ ·123	− ·123	= − ·14	− ·14
28	+ ·241	+ ·079	− ·140	= + ·70	+ ·70

Normal Equations.

+1·622ΔA′	+0·060ΔD′	−0·089Δα	+ 0·395Δβ	= −0·108
+0·060	+2·780	+0·118	+ 6·264	= +0·019
−0·089	+0·118	+0·183	− 0·801	= +0·016
+0·395	+6·264	−0·801	+20·5	= −0·023

TABLE IV.

Normal Equations derived by combining the Equations of Table II. and those of Table III.

25·311ΔA′	+ 2·563ΔD′	+0·797Δα	+ 0·790Δβ	= +0·775
2·563	+ 8·686	+0·159	+12·528	= +0·321
0·797	+ 0·159	+8·074	− 1·602	= +0·555
0·790	+12·528	−1·602	+40·100	= −0·046

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